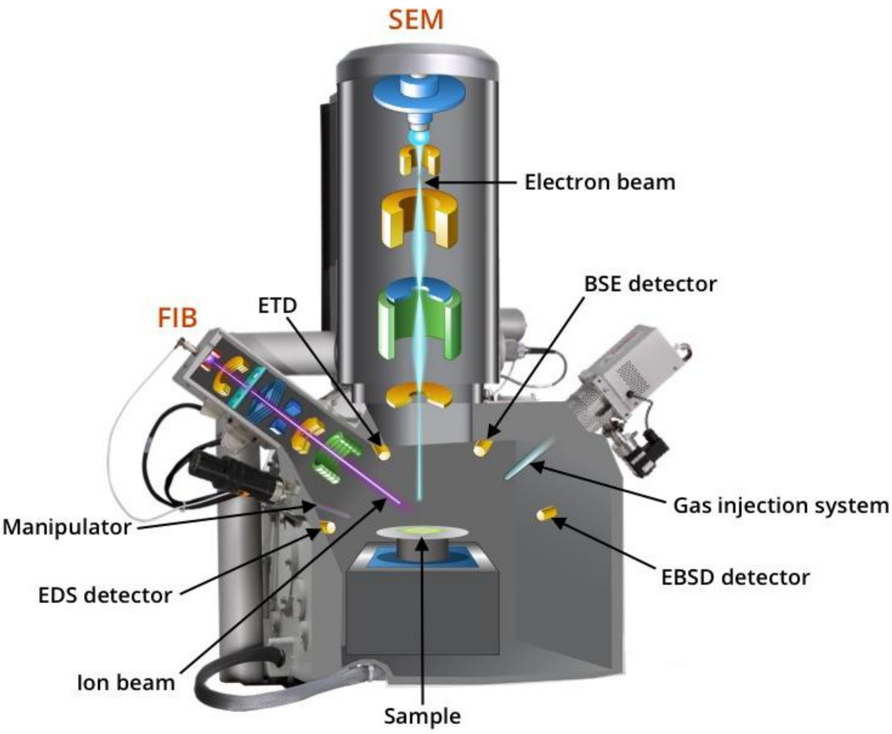
Focused Ion Beam Machining

- By Ritwik Jain (244103208)



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1. Introduction

Richard Feynman suggested in 1959 that one-day technology would exist that could be used as our eyes and tools in the microscopic world. He anticipated the use of concentrated ion beams to help see and control matter at the smallest scales, in his lecture "There is plenty of space at the bottom" (Feynman, 1960), which is often regarded as the genesis of nanotechnology. It took another 40 years before the first widely accessible Focused Ion Beam/Scanning Electron Microscope (FIB/SEM) was available (Young and Moore, 2005). Gallium FIB/SEMs, which combine a scanning electron microscope and a focused ion beam in a single device, have since become essential tools in many institutions and laboratories.

Although tiny silicon devices can be developed using photolithography technology, today's nanoscale devices must also use other materials. One of the most recent processing methods is a focused ion beam (FIB) machining, which first became
widely accessible in the 1990s. Currently, transmission electron microscopy (TEM) sample preparation and semiconductor manufacturing are the two primary applications for FIB processing. It is an essential instrument for design work, failure analysis, lithographic mask repair, device cross-sectioning, maskless implantation, and ion beam-aided etching. Recently, it has been used in a scanning electron microscope (SEM), 3-dimensional patterning with high precision, and improved material removal in microelectronic applications. The fabrication of small structures using FIB technology can create items with micro- or nanoscale features. This in turn sparked study into the fabrication of three-dimensional objects at the micro- and nanoscale. High resolution imaging has become essential when FIB emerges from failure analysis and replacement mask, particularly towards fabrication. It was essential to use an SEM to examine the ion milled surfaces, hence, FIB and SEM merging has been achieved. Without losing the benefits of each column, milling, deposition, and high-resolution imaging

with damage-free imaging are all feasible. To halt the milling operation precisely at the required depth, an ion beam cutting system and an electron beam observing system will be useful (Robert, 1999).

Focused Ion Beam (FIB) machining has become a critical tool in advanced materials science, nanotechnology, and semiconductor research due to its unique ability to both modify and analyse materials at the micro- and nanoscale. FIB technology employs a finely focused beam of ions, typically gallium, which interacts with a sample surface to achieve precise material removal, deposition, or structural modification. This enables FIB to fulfil roles in fabricating nanostructures, preparing samples for high-resolution microscopy, and prototyping microelectronic components.
The versatility of FIB is rooted in its ability to selectively manipulate materials, allowing scientists and engineers to explore complex material behaviours and design innovative structures with unparalleled precision. Traditional methods of machining and analysis are limited when it comes to features on the nanometre scale, where even minor inaccuracies can significantly impact device performance. FIB addresses these limitations by offering a controlled means of working at the nanoscale, thereby expanding the possibilities for research and application in various domains.
This project aims to explore the principles and applications of FIB machining, detailing its mechanisms, operational parameters, and real-world uses in fields such as microelectronics, materials science, and nanotechnology. Key areas of investigation include material removal and deposition, sample preparation for Transmission Electron Microscopy (TEM), and circuit editing. Additionally, recent advancements and challenges in FIB technology, including integration with other analytical methods and the development of new ion sources, will be examined to provide a comprehensive view of its evolving role in modern science and industry.
Through this project, we intend to highlight the impact of FIB techniques on advancing material characterization, device fabrication, and prototyping capabilities, thus underscoring its importance as a versatile tool in both academic and industrial settings.

As technology advances toward increasingly miniaturized devices and high-performance materials, the demand for precise, nanoscale modification and analysis techniques has surged. Focused Ion Beam (FIB) machining has emerged as an indispensable tool that meets this demand, allowing for intricate material manipulation with nanometre-scale precision. Originally developed for the semiconductor industry, FIB technology is now widely used in a variety of fields, including materials science, nanotechnology, and even biological sciences, owing to its remarkable versatility.

At the core of FIB technology is its ability to generate a highly focused beam of ions, usually gallium, which can selectively interact with the surface of a sample. This focused beam provides multiple capabilities:

- Material Removal: FIB can precisely mill or etch away material, enabling the creation of complex structures or cross-sections for internal examination.
- Deposition: In addition to removing material, FIB can deposit materials by introducing gas precursors, allowing for the addition of protective coatings, conductive paths, or other functional layers.
- Imaging and Analysis: FIB is often paired with other techniques, such as Scanning Electron Microscopy (SEM) or Energy-Dispersive X-ray Spectroscopy (EDS), to provide detailed compositional and structural information at high resolution.

The unique ability to perform such a range of operations at nanoscale precision has made FIB a powerful tool for both analysis and fabrication, from preparing TEM samples to editing circuit elements in microelectronic devices. Additionally, FIB is invaluable for rapid prototyping in research and development, where its speed and accuracy help in fabricating and testing novel micro- and nanoscale structures.

This project delves into the working principles and technical nuances of FIB machining, including:

1. Fundamental Mechanisms: Understanding the ion-solid interactions and how beam parameters (such as energy, current, and focus) influence precision and accuracy.
2. Applications in Various Fields:

    - Material Science: FIB’s role in preparing samples for advanced microscopy and in the characterization of internal material structures.
    - Nanotechnology: The fabrication of nanoscale devices, including quantum dots and nanowires.
    - Semiconductors and Electronics: Circuit editing, defect analysis, and repair in microelectronic components.
3. Advancements in FIB Technology: Highlighting recent developments, such as new ion sources (e.g., helium, neon), dual-beam systems (FIB-SEM), and the integration of automation for increased efficiency.
4. Challenges and Limitations: Exploring the limitations of FIB, including ion-induced damage, potential contamination, and costs associated with system complexity and maintenance.

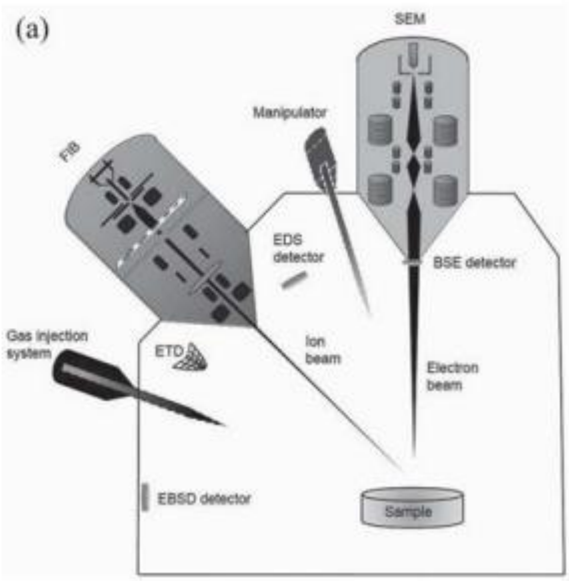
The ability of FIB to modify, analyse, and image materials at nanoscale precision has enabled significant breakthroughs across multiple disciplines:

- In materials science, FIB assists in studying the microstructures of advanced materials, enabling researchers to make connections between microstructure and properties.
- In nanotechnology, it supports the creation of complex nanostructures and devices that form the foundation for innovations in quantum computing, photonics, and biomedical devices.
- In electronics, FIB enables rapid testing and modification of prototypes, providing valuable insights and solutions during device development and debugging processes.

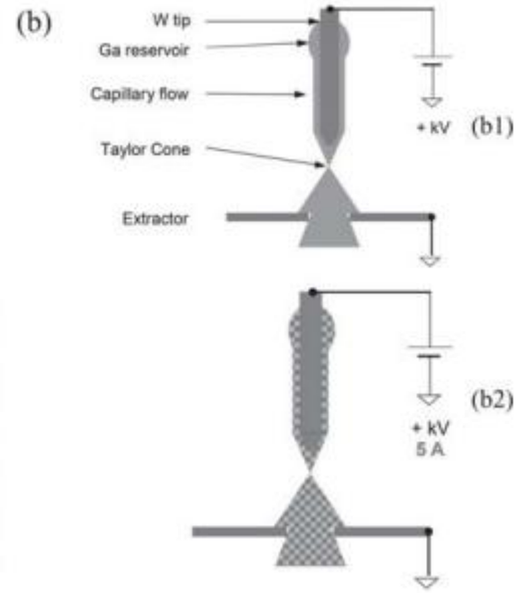
In this project, we seek to offer a comprehensive analysis of FIB techniques, emphasizing their transformative impact on research and industry. By addressing both current capabilities and future potential, we aim to underscore the significance of FIB as a tool that continues to shape technological progress in diverse fields.

2. Basic FIB Equipment

Figure below depicts a standard FIB configuration. Multiple detectors and lens detectors are included in FIB. FIB frequently have manipulators and gas insertion system. Liquid metal ion sources (LMIS), particularly gallium ion sources, are used by most FIB systems.



2 A typical FIB/SEM system. FIB/SEMs combine a SEM and a FIB into a single apparatus, and they frequently come with a variety of detectors, such as ETD, BSE, EDS, EBSD, and in lens detectors. On FIB/SEMs, manipulators and gas injection devices are frequently found



1) Schematic showing the differences between a Ga-LMIS, , in which melting the source metal doesn't require any Heating current, and an LMAIS filled with a eutectic alloy, which needs the tip to be heated with a 5 A current to enable ion emission of both ion species.

There is also ion generators based on pure gold and iridium. In a gallium LMIS, heated gallium metal is put in contact with a tungsten needle. The heated gallium wets the needle, flows to the tip, and is then formed into a Taylor cone (Figure 2) by the conflicting forces of surface tension and the electric field. This cone's point radius is incredibly tiny (about 2 nm). The gallium atoms are ionized and emit electromagnetic fields because of the intense electric field at this tiny point. The source ions are then typically focused onto the sample by electrostatic lenses after being accelerated to an energy of 1–50 keV. LMIS creates ion beams with a very tiny energy dispersion and high current density. A contemporary FIB can image a sample with a spot size of a few nanometres or send tens of nanoamperes of current to a sample. Gallium (Ga) is primarily used as a liquid metal ion source (LMIS) in FIB systems for the reasons listed below evaluated the efficacy of liquid metal ion sources – Al, Ga, In, Au, and B.

• Ga has a reduced melting point (Tm = 29.8° C), allowing for a small design and minimal heating.
• Ga has low fluctuation, which prolongs source life. • Ga's low surface free energy encourages sticky behaviour, which encourages substrate soaking.
• Ga's favourable emission properties allow for high rotational intensities and a narrow energy distribution.
• High luminosity and favourable flow characteristics.
• Its mass is almost perfect because the larger components can be milled thanks to their weight.

Instruments that use plasma beams of noble gas ions, like xenon, have lately become more commonly accessible. To expand LMIS to ion species other than Ga, very early and vigorous efforts have been made. For instance, switching N to P dopants released from the same liquid metal alloy ion source would enable semiconductor dopant implantations (Bischoff et al., 2016). The need to choose appropriate ion species for doping or sample processing, friendly methods for better control of ion-induced population, selective insertion of ion species, or the need for particle deposition, are all made possible by the FIB system. To achieve this, an ongoing endeavour has been made to broaden the LMIS to other metals and alloys over the years, opening the door to the potential of up to 46 different ionic species.

2.1 PRINCIPLE

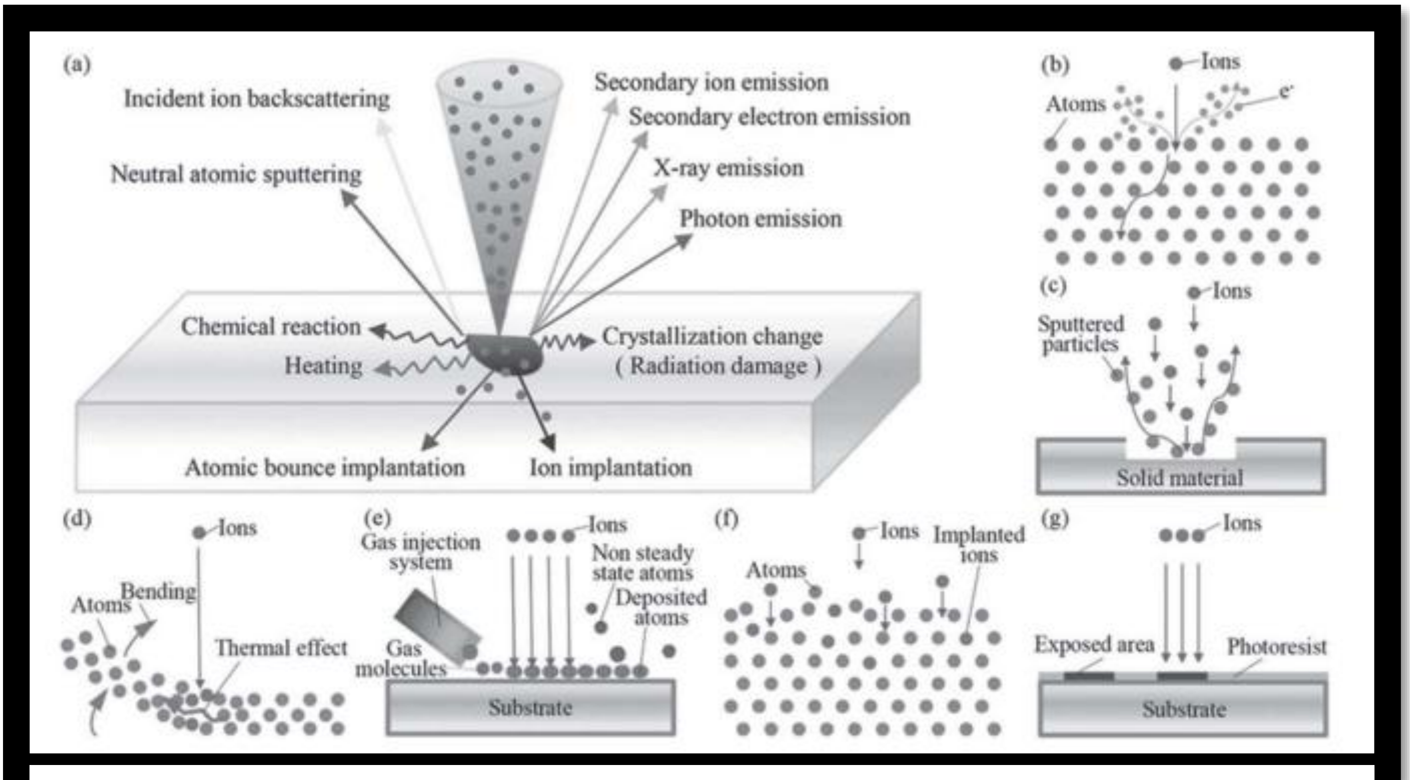
FIB systems operate in a similar fashion to a scanning electron microscope (SEM) except, rather than a beam of electrons and as the name implies, FIB systems use a finely focused beam of ions that can be operated at low beam currents for imaging or at high beam currents for site-specific sputtering or milling. The gallium (Ga+) main ion beam strikes the sample surface as shown in the diagram on the right, and a tiny quantity of material sputters out, leaving the surface as secondary ions (i+ or i) or neutral atoms. Secondary electrons (e) are also produced by the mainstream. The information from the sputtered ions or secondary electrons is gathered as the main beam roasters on the sample surface to create an image.
Modern FIB systems can readily achieve 5 nanometre imaging resolution at low main beam currents because very little material is sputtered (imaging resolution with Ga ions is restricted to 5 nm by sputtering and detector efficiency). Sputtering can eliminate a significant amount of material at greater main currents, enabling accurate milling of the specimen down to a submicrometric or even a nanoscale. The interplay between the energetic ions and the solid material's centre or electrons when the ion stream bombards its surface can result in a variety of physical and chemical events. Therefore, a succession of events may take place, as illustrated in Figure 3, including backscattering, implantation, excitation, amorphization, sample heating, and chemical reactions, in addition to the solid atoms being sputtered out. As a result, mastering the fundamentals of ion-solid interactions could significantly improve one's capacity to create superior nanostructured surfaces using FIB nanofabrication technology. From the viewpoint of ion energy, the occurrence of the ion-solid interactions can be seen as a group of elastic collision and inelastic collision events. Consequently, the following intriguing features can be seen in Figure 3a. When an elastic impact takes place between an incident ion and a target atom within a collision cascade area, incident ions are reflected to create

backscattered ions. The energy of the incoming ions is transmitted in part to the colliding atoms to produce secondary electrons (SEs) and X-rays, while the target atoms are energized and ionized to produce visible light, ultraviolet light, and infrared light when an inelastic impact takes place. Additionally, the solid substance surface can release secondary ions when the incident ions attack it (see Figure 3b).

These phenomena can carry out tasks like spectrum analysis and ion beam photography. If the kinetic energy delivered by the ions is large enough to exceed the surface binding energy, the collision process can cause the target atoms of the solid lattice to become off-site atoms, which may pass through the lattice gap and be ejected as sputtered particles from the surface of the material (see Figure 3c). To create tension or strain, the target material is subjected to ion implantation and material amorphization, which may also cause the target material's structure to distort (see Figure 3d).
Ion beam deposition can be carried out by adding external circumstances, such as gas molecules when the energy supplied by the ions is less than the surface binding energy (see Figure 3e). Another scenario is that the incident ions may impart energy and velocity to the atoms affixed to the solid material's surface, causing the atoms to penetrate the solid material further.
The primary processes of ion implantation involve these two physical collisions, both of which alter the material's surface characteristics (see Figure 3f). Elastic impact or inelastic collision can also start chemical reactions in the solids, and the latter is particularly important in such chemical reactions if the irradiated substance is a compound. A low-energy electron deluge cannon can be used to provide charge neutralization if the material is non-conductive.

In this way, even highly insulating materials can be imaged and milled without a conducting surface layer, as would be necessary in an SEM, by imaging with positive secondary ions using the positive primary ion stream. Up until lately, the semiconductor sector was where FIB was most widely used.

Applications like defect analysis, circuit alteration, photomask repair, and the production of site-specific TEM samples for integrated circuits have all become standard practices.
Modern FIB systems have high resolution imaging capabilities, and when Focused Ion Beam Machining as a Technology for Long Term Sustainability combined with in situ sectioning, they have often rendered unnecessary the need for SEM examination of FIB sectioned materials (Aravindan et al., 2010). SEM imaging is still needed for the

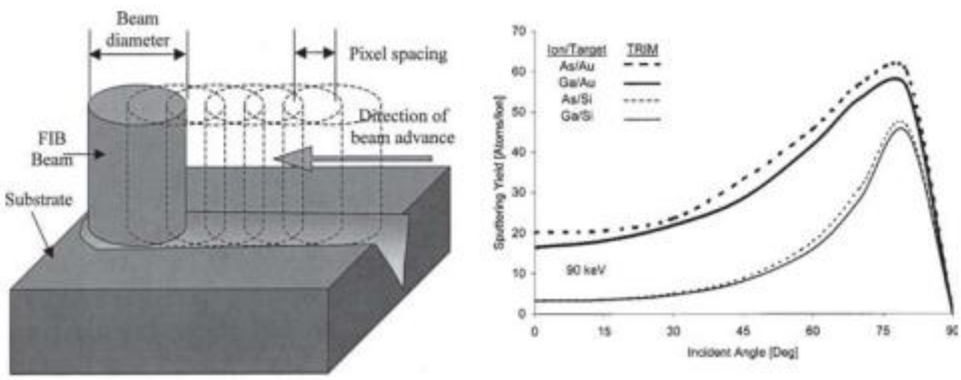


3 The fundamental method by which the ion stream interacts with a solid substance is shown in (a). Schematic representations of the tiny interaction process between ions and atoms or molecules in lithography, etching, irradiation, deposition, implantation, and (b) imaging are shown in figures (b) through (f)

greatest resolution imaging and to avoid harm to delicate samples. However, the advantages of both can be used when SEM and FIB columns are attached to the same room.

2.2 PROCESS PARAMETERS IN FIB PROCESS

Modern FIB machines are computer-controlled, and grinding is done with exact pixel-by-pixel movements. The procedure, also referred to as a computer scan, is roughly depicted in Figure 4. The FIB tracks a string of neighbouring pixels that indicate the channel's contour to mill a submicron channel. Ion flow, fluence, dose, beam current, and current density are the main terms used to characterize the properties of an ion beam. The temporal rate of energy movement is known as flux. The quantity of particles moving through a specific region in a particular amount of time is known as flux. The ions/cm^2 measure flux. The word "dose" refers generally to the amount of radiation or particle absorption by a material. The same measure of fluence applies to dose. The quantity of ions that travel through a specified area before striking an object within that area is known as fluence. The range of the beam current is a few pA to several nA. The energy level or quantity of ions in each region at any given moment is measured by the current density.



4 *(a) Schematic of FIB milling, (b) Angular dependence of sputtering yields of 90 keV As and Ga ions on Au and Si targets.*

It uses the columns/cm2 measure. The relationship between beam current, dwell point spacing, and dwell duration determines how many ions are given to the substrate per unit area (ion dose). For a specific substrate substance, the ion dose can be converted into the profundity of sputtering. The Ga+ beam current, stay duration, and pixel size together decide the pixel dosage or the number of ions per unit area. The tiniest element of a digital picture is typically a pixel. The Ga+ beam current, machine zone size, and machining duration are used to calculate the overall Ga+ dosage. Scanning is the technique used to trace tightly separated parallel lines for sputtering. The TRIM modelling of the relationship between the sputtering yield and incident angle at a 90 keV ion energy
in the sputtering of Au and Si surfaces is shown in Figure 4b. In the modelling, a 90 kV electric potential is used to single charge and energize the As and Ga atoms. According to Figure 4b, for all instances taken into consideration, the sputtering yield increases as the incidence angle increases until it hits its maximum near 80°, at which point it quickly declines to zero as the incident angle approaches 90°. Figure 4b also demonstrates that while the equivalent sputtering yield for the Au substrate rises less, that of the Si substrate increases roughly ten times from the normal incidence to the angle at its apex.

3. MULTI-PROCESS CAPABILITY OF FIB

3.1 FIB ETCHING –

FIB is intrinsically harmful to the specimen, unlike an electron microscope. The sample will discharge atoms from the surface when the high-energy gallium ions hit it. Additionally, the upper few nanometres of the surface will be injected with gallium atoms, causing the surface to become porous. The FIB is used as an instrument for micro- and nano-machining materials at the micro- and nanoscale because of its sputtering capacity. Although FIB nano milling is still in its infancy, it has grown into a sizable subfield of its own. Typically, 2.5–6 nm is the lowest beam size for imaging. The interactions between the milling sample and the overall beam size determine the size of the tiniest milled features, which are slightly bigger (10–15 nm).

3.2 GAS ASSISTED FIB DEPOSITION –

Ion beam induced deposition can also be used with a FIB to place substance. When a gas, such as tungsten hexacarbonyl ($W(CO)_6$), is introduced to the vacuum container and permitted to chemisorb onto the sample, FIB-assisted chemical vapor deposition takes place. The precursor vapor will split into volatile and non-volatile components as the laser scans an area, The non-volatile component, like tungsten, deposits on the surface. This is advantageous because the metal can be used as a protective layer to shield the sample beneath from the beam's harmful sputtering. Metal bands of any length, from nanometres to hundreds of micrometres, can be deposited using tungsten. A local deposition is also a possibility for other elements like platinum, cobalt, carbon, gold, etc. Table below summarizes the different precursor gases used for depositing different materials.

FIB Deposition Precursor Gases

S. No.	Element to Be Deposited	Precursor Gas
1	Carbon	Phenanthrene
2	Platinum	Tri methyl cyclo penta dienyl platinum
3	Tungsten	WCO_6 Tungsten hexa carbonyl
4	SiO_2	O_2 and tetra methoxy silane or O_2 and tetraetoxysilane
5	Aluminium	Trimethylamine alane

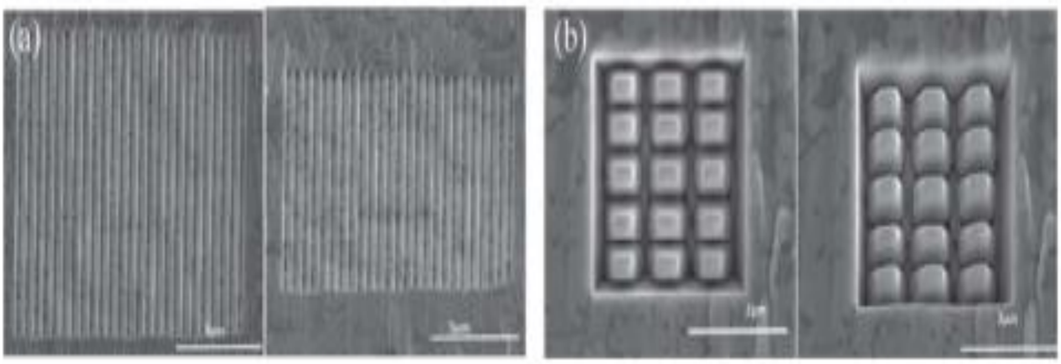
In the semiconductor business, FIB is frequently used to patch or alter an existing semiconductor device. The gallium beam, for instance, could be employed in an integrated circuit to remove undesirable electrical connections and/or to apply conductive substance to create connections. In patterned doping of semiconductors, the high degree of surface contact is taken advantage of. FIB is also employed for insertion without a covering.

3.3 FIB Tomography –

A potent instrument for site-specific 3D imaging of sub-micron characteristics in a material is now the focused ion beam. In this method of FIB tomography, the sample is successively milled with an ion beam pointed perpendicular to the specimen while an electron beam images the freshly exposed surface. Larger size nanostructures can be characterized using this so-called "slice and view" method in a variety of SEM imaging modalities, such as secondary electron, backscattered electron, and energy dispersive X-ray measurement. Since the object is being progressively milled away after each picture is taken, the procedure is destructive. After recording the picture stack and eliminating artifacts, the gathered sequence of images is then converted into a 3D volume. Ion mill curtaining, where mill patterns create broad aperiodic bands in each picture, is the main artifact that impairs FIB tomography. De-striping methods can be used to eliminate the ion mill curtaining. FIB tomography can be carried out on materials and living samples, and at both ambient and cryogenic conditions

4. Application of FIB System

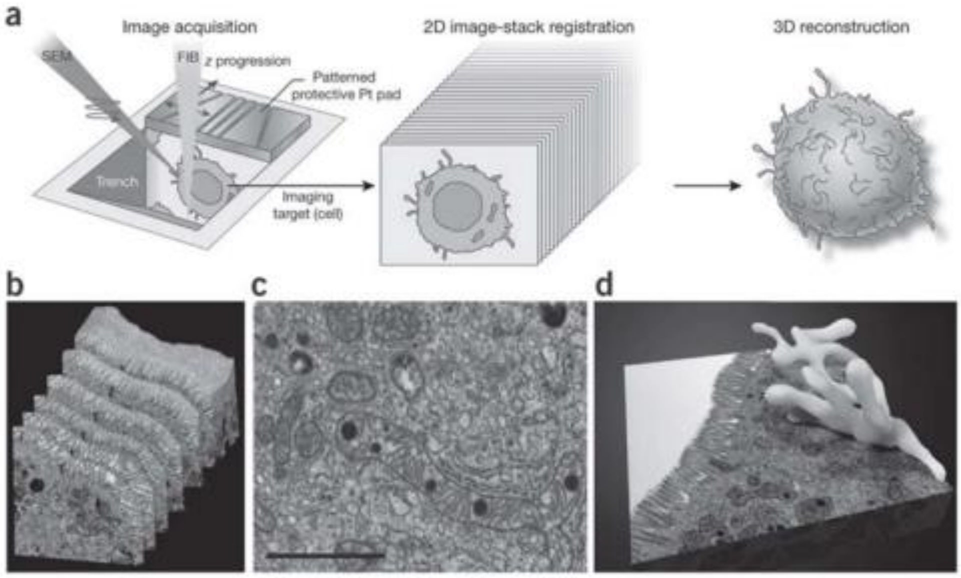
Figure 5 shows how FIB milling has been applied to micro-nano fabrications. The development of tools and dies for micromachining, micro forming, useful surfaces through surface structuring, the creation of microsurgical instruments, etc., all make use of high ion momentum beams. In comparison to a cutting tool without any structures, the microtextured cemented carbide tool greatly lowers the cutting force by 28% when used for traditional machining of aluminium alloy. By decreasing the chip-tool contact length, the macrotextures serve as a lubricant reservoir and lessen friction at chip-tool surfaces. FIB-SEM have been widely used for recording live 3D imaging of substantial living materials in recent times.
The 3D images of live cells are shown in Figure 6. Table below summarizes the how different functionality of FIB can be used for different applications.



5 *250 nm pitch and depth nanogrooves (FIB process parameters: 30 keV, 0.5 nA, rest time: 10 s, incidence angle: 0°).*

(a) Top perspective with a 20° angle. (FIB process parameters: 30 keV, 0.5 nA, rest time: 10 s, angle of incidence: 0°) Nanopillar array with 500 nm side length and 500 nm depth

(b) upper image with a 20-degree tilt



6 *FIB-SEM 3D imaging of substantial living materials. (a) Large biological samples are inserted into the FIB-SEM apparatus after being traditionally fixed (by aldehydes) or cryogenically fixed (by high-pressure refrigeration), stained with heavy metals, resin embedded, and mounted. Here, selected sample regions are "trenched" to expose the region of interest. The region of interest is then imaged using a SEM (blue beam) and FIB (yellow beam) to create a 2D image stack after a repeated cycle of resin milling. The material to be scanned is protected by a patterned platinum (Pt) pad that enables automated beam adjustment and slice-thickness control. The 3D structure of interest is then revealed by mathematically converting the 2D picture stack to a 3D volume, aligning, and segmenting it. (b–d) A rodent intestinal sample was used as a typical case of 3D tissue imaging. An image stack (b), a chosen slice through the stack (c), and a segmented depiction of a mitochondrion with many branches that is present in the scanned volume are all displayed. (d) 1 millimetre scale marker*

The most typical function is milling. These tools have a wide range of applications, including the production of atomic force microscope tips, the creation of nanopillars for mechanical testing, the cross-sectioning and failure analysis of integrated circuits, and the fabrication of nanostructures for devices and sensors.

An Overview of 3D Nanostructure and Device Manufacturing Using FIB Nanofabrication

FIB Assisted Processes	Application Field	Typical Components
Etching	Semiconductor devices and large-scale integrated circuits, sample detection, high-power solid-state laser, renewable energy, nano-optics, single molecule detection	Optical mask, transistor, chip, TEM samples, crack detection, micro-sensor, nanosensors, etc.
	Sample detection, integrated circuits, MEMS, nano-optics, optoelectronic devices, molecular devices, Raman spectroscopy, electrochemical, biomedical	Gold electrodes, third-generation DNA sequencers, advanced extreme ultraviolet lithography mask repair, etc.
	Electrical, optical, optoelectronic platform, magnetic, medical diagnosis, MEMS, solar–thermal energy harvesting system	Resonator, Fresnel zone plates, multifeatured shaped 3-dimensional nanostructures, silicon nano-line structure, ordered nano-textured surface, surface optical functional texture of crystalline silicon cells, etc.
Deposition	Integrated circuit, nano-optics, nanoplasmonics, electronics, nanosensing, microelectrode system, microfluidics, semiconductors and nanosuperconductor, complex surface structures	Optical masks, X-ray masks, and optical phase masks, ohmic contact layer, connection line, diffraction grating, nanochannels and hollow nanowires, micro-hemispheres, parabolic and sinusoidal microstructures, etc.
Implantation	Nanoelectronics, nanophotonics, plasmonics, sensing, biomedical, circuitry, semiconductor, surface modification, nano-cutting, device performance regulation, size analysis, and new device production	optical waveguide, nanochannels, freestanding bridges and cantilevers, resonators, suspended beams, silicon-based nanostructures, micro-pyramid anti-reflection layer, micro-pillar array, InGaZnO thin-film transistors, thin circuitry, etc.

5. Future Developments and Innovations

Advanced Ion Sources:

- Researchers are exploring alternative ion sources beyond gallium, such as helium and neon ions in Helium Ion Microscopy (HIM) systems. These lighter ions provide higher spatial resolution and cause less damage, making them suitable for ultra-fine machining and imaging.

- Multi-ion sources, allowing for rapid switching between different ions, are also being developed to enhance the versatility of FIB systems.

3D Nano printing:

- The combination of FIB with additive manufacturing techniques is leading to the development of 3D nano printing capabilities. This involves layer-by-layer deposition of materials to create complex 3D nanostructures, potentially revolutionizing fields like nanophotonic and metamaterials.

Automated and AI-Driven FIB:

- Advances in automation and artificial intelligence (AI) are being integrated into FIB systems to improve precision, reduce human error, and increase throughput. AI-driven pattern recognition and process control can optimize machining parameters in real time, enhancing the efficiency of complex tasks.

Focused Ion Beam machining is a cornerstone of modern micro- and nanofabrication, offering unparalleled precision and versatility. However, its successful application requires a deep understanding of the underlying physics, careful control of process parameters, and continuous innovation to overcome its inherent limitations.

Several universities around the world are conducting cutting-edge research involving Focused Ion Beam (FIB) techniques. Here are some notable institutions:

1. MIT (Massachusetts Institute of Technology), USA

- Department: Department of Materials Science and Engineering (DMSE)
- Focus: FIB is used for nanofabrication, material characterization, and device prototyping in various research projects.
- Notable Research Groups: Nanostructures Laboratory (NSL), Microsystems Technology Laboratories (MTL)

2. Stanford University, USA

- Department: Stanford Nano Shared Facilities (SNSF)
- Focus: FIB is utilized for semiconductor device research, nanofabrication, and material analysis.
- Notable Research Groups: Stanford Nano characterization Laboratory (SNL)

3. University of Cambridge, UK

- Department: Department of Engineering, Nanoscience Centre
- Focus: Research on nanostructuring, FIB-based TEM sample preparation, and ion-beam-induced deposition.
- Notable Research Groups: Nanomaterials and Spectroscopy Group, Electron Microscopy Group

4. University of Oxford, UK

- Department: Department of Materials
- Focus: FIB is employed in the study of materials at the atomic scale, particularly in the areas of metallurgy and condensed matter physics.
- Notable Research Groups: David Cockayne Centre for Electron Microscopy

5. ETH Zurich, Switzerland

- Department: Department of Materials Science
- Focus: Advanced FIB techniques for 3D nanofabrication, material analysis, and semiconductor research.
- Notable Research Groups: Electron Microscopy Center, Laboratory for Nanometallurgy

6. Harvard University, USA

- Department: School of Engineering and Applied Sciences
- Focus: FIB is used for interdisciplinary research, including nanotechnology, biology, and materials science.
- Notable Research Groups: Harvard Center for Nanoscale Systems (CNS)

7. University of California, Berkeley, USA

- Department: Department of Electrical Engineering and Computer Sciences (EECS)
- Focus: FIB is applied in the development of micro- and nanodevices, as well as in material characterization.
- Notable Research Groups: Berkeley Nanosciences and Nanoengineering Institute (BNNI)

8. Tsinghua University, China

- Department: Department of Materials Science and Engineering
- Focus: FIB research focused on nanomaterials, device fabrication, and advanced microscopy techniques.
- Notable Research Groups: Nanostructured Materials Lab, Electron Microscopy Lab

9. National University of Singapore (NUS), Singapore

- Department: Department of Materials Science and Engineering
- Focus: Use of FIB for nanoengineering, semiconductor research, and material science.
- Notable Research Groups: Centre for Advanced 2D Materials (CA2DM)

10. Tokyo Institute of Technology, Japan

- Department: School of Materials and Chemical Technology
- Focus: FIB applications in nanotechnology, materials analysis, and microelectronics.
- Notable Research Groups: Nano-Materials Design Laboratory, Laboratory for Advanced Materials

These universities have state-of-the-art facilities and are leaders in research involving FIB techniques, contributing to advances in materials science, nanotechnology, and semiconductor technologies.

6. Summary

Future materials can now be researched and developed using a variety of ion species and focused ion beams (FIBs). From site-specific cross-sectioning and 3D models to TEM lamellae preparation, nanofabrication, and defect engineering, there is an FIB tool for every application field. The choice of the best ion species/system for the job is aided by the basic physics of ion solid interactions as well as the system's available tools (such as gas injection systems, manipulators, and detectors). Virtually any material type can be milled and viewed in a fluid manner, down to submicron to nanometre scale. Due to its higher precision and reduced lateral scatter, FIB is preferable to other micromachining methods when compared.

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